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Estimating the Reliability of Advanced Waste Treatment

Southwest Ohio Regional Computer Center, Cincinnati

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16. ABSTRACT

Daily operating data from South Lake Tahoe covering six years of continuous operation together with shorter records from other plants have been analyzed. The data are skewed but can be normalized by conversion to logs, thus permitting estimates of long-term reliability based on normal statistics. A spread factor, S, which is the antilog of the standard deviation is shown to be a useful parameter for estimating future performance. Spread factors lie between 1.5 and 2.0 for all the parameters studied except MPN. The Ely, Minnesota, plant on Shagawa Lake produces an effluent that has approximately one tenth the concentration of phosphates obtained by other AWT plants, but the spread factor is about the same for all plants.

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Estimating the Reliability of Advanced Waste Treatment

by Robert B. Dean, Science Advisor, EPA
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The following article describes the analysis of data to estimate long-term reliability of advanced waste treatment based on normal statistics. The data analyzed included daily operating data covering six years of continuous operation at the South Lake Tahoe waste treatment plant plus records from other plants.

Waste treatment plant performance is commonly reported in terms of average values covering periods measured in weeks, months or even years. The average value of a parameter such as phosphate concentration multiplied by the time period and the average flow provides a rough estimate of the total quantity of phosphate discharged. The average value gives no information regarding the reliability of a plant.

In pollution control we are interested in the probability that a given process will exceed an established standard. Obviously, the average concentration discharged must be below the standard because there will be variations above and below the average. If we can find an expression that gives the fraction of the time that a given concentration has been exceeded in the past, we can predict the future performance of the plant provided it continues to operate in the same way. We may also be able to predict how much the basic process must be altered to meet a more stringent requirement.

The reliability of any process must be described by at least two numbers. If the distribution of the results is normal, then it can be completely described by the average and the standard deviation. Most of the statistical procedures used to evaluate data assume that the population will be normally distributed. In many cases, this assumption is not met, particularly for concentrations of trace substances where values less than zero have no meaning. Several natural populations obey a lognormal distribution in which the logarithms of the values are normally distributed.[1,2] Metal concentration in sludges[3] and the usual measurements of pollutants in wastewater are all lognormally distributed.[4]

The lognormal distribution has a strong theoretical justification based on the concept that fluctuations are proportional rather than additive. Most apparently normal distributions, such as the heights of adult males, are equally well fitted by a lognormal distribution. Whenever the standard deviation is a significant fraction of the average, the distribution is probably lognormal rather than normal.

If the population can be fitted by a lognormal distribution, we can make predictions about future performance with a high degree of confidence provided that the process is in statistical control. The term "statistical control," is used to describe a population whose variations appear to come from consistent causes.[5,6] In practice, a process can be subject to occasional violent upsets and still follow lognormal statistics closely because the frequency of upsets is usually inverse to their magnitude. However, if a plant is significantly altered, for example by the addition of a new unit process half way through the series, one cannot expect to describe it by any simple distribution.

The easiest way to test a population for conformance to the normal curve is to plot the cumulative distribution function on a scale that produces a straight line if the distribution is normal.[7] Probability paper is designed to facilitate plotting ranked data against the fraction or percent of the number of observations so that normal distributions will approximate a straight line.

Deviations from the straight line can be used to test for conformity to the normal curve. A useful approximation based on the work of Kolmogorov and Smirnov[8] states that if any point on the cumulative distribution departs from the line of best fit by $.886/\sqrt{N + 1.5}$ where N is the total number of observations, there is less than a five percent chance that the population is in fact normal. If the deviation exceeds $1.03/\sqrt{N + 1.5}$, there is less than one percent chance of normality.

To plot a cumulative probability curve, the data must first be arranged in ascending order of magnitude. The fraction of the population less than and the fraction greater than any recorded value is plotted on the x axis against the value on the y axis. This procedure produces a series of steps that, conventionally, have been joined by vertical lines as shown in

Table 1

South Lake Tahoe - Requirements for Export

Description	Alpine Co.	Lahontan R. W. Q. C. B. percent of time		
		50	80	100
MBAS, mg/l, less than	0.5	0.3	0.5	1.0
BOD, mg/l, less than	5	3	5	10
COD, mg/l, less than	30	20	25	50
Susp. S., mg/l, less than	2	1	2	4
Turbidity JU, less than	5	3	5	10
pH, units	6.5 to 8.5	6.5 to 9.0		
Coliform, MPN/100 ml	Adequately Disinfected	Median less than 2 Max. No. Consecutive samples greater than 23, 2		

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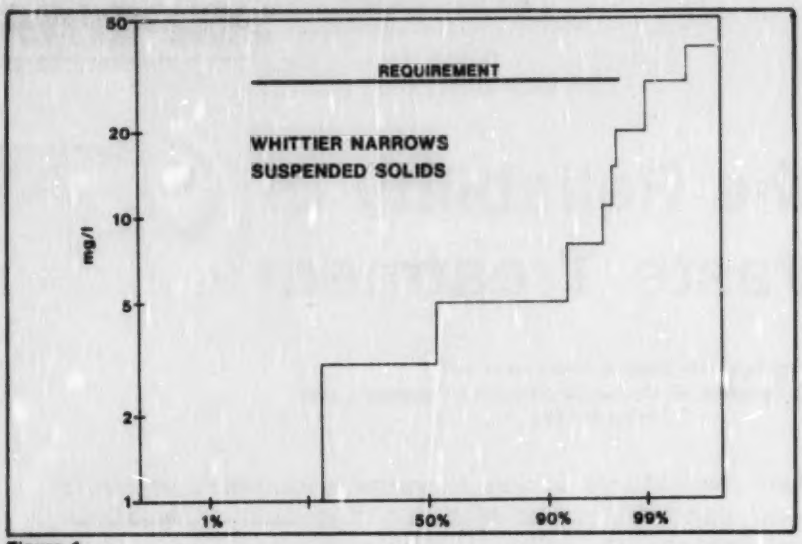


Figure 1

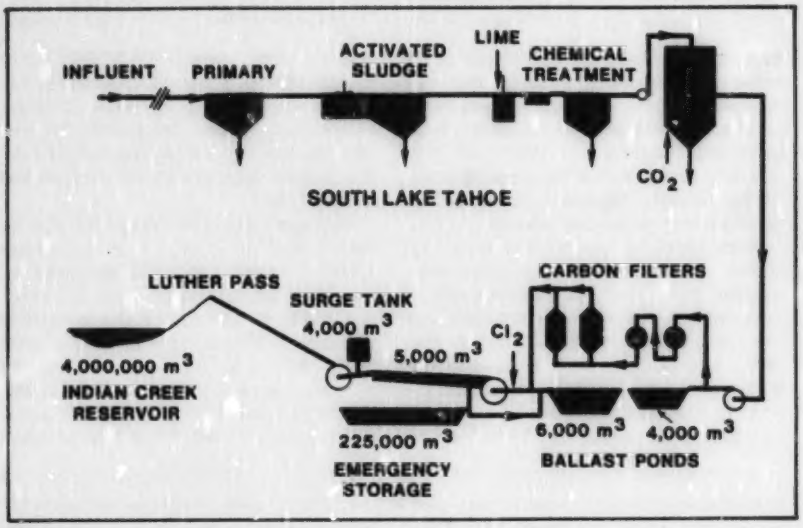


Figure 2

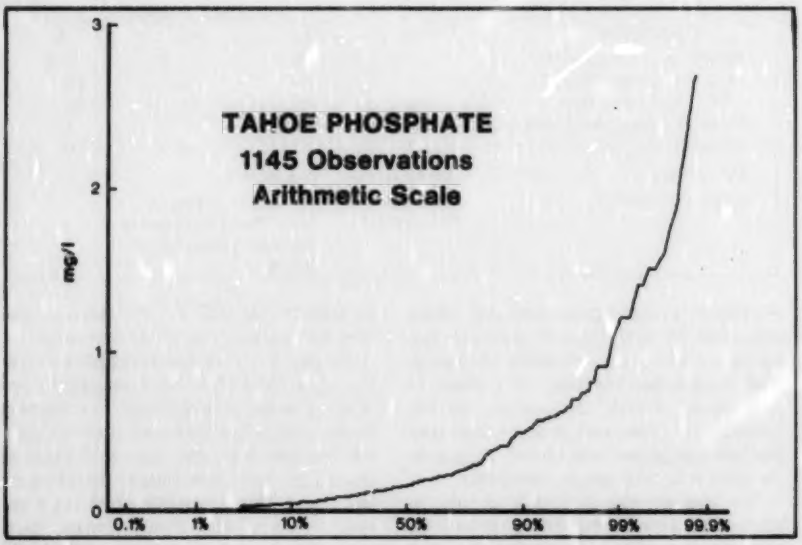


Figure 3

Figure 1. When there is a large quanity of data to be plotted by computer, it is convenient to plot each y value only once. The best plotting position is then given by the function x/N + 1 where n is the serial or rank value of the observation.[7] This function puts all of the data on the chart whereas it is imposaible to plot either the zero or 100 percent points since they lie at plus and minus infinity

The line of best fit will pass close to the average value at the 50 percent ordinate and will have a slope proportional to the standard deviation of the population. The average $\bar{y}$ plus and minus one standard deviation, s, will be at 84.13 and 15.87 percent, respectively; $\bar{y}$ + 2s will be at 97.73 and 2.27 percent.

If the population is not normally distributed, the data will lie along a curve that deviates from a straight line by more then the Kolmogorov-Smirnov ratio. Such deviations are most obvious at the low end of the curve. If the standard deviation, s, equals the average, $\bar{y}$, then $\bar{y}$ - s will be zero, and 15.87 percent of the data should have negative values. When the data are concentrations of pollutants, it is quite common to find s approximately equal to $\bar{y}$, yet negative values of concentration have no meaning. The conclusion is that the data are not normally distributed.

When conversion to logarithms normalizes the population, the full power of statistical methods can be applied with confidence to the converted data. Conveniently, if a population of measured quantities that cannot admit negative values appears to obey normal statistics, it will also obey lognormal statistics.

The advantage of normal over lognormal statistics in the past was ease of computation. With modern computers and pocket calculators, conversion to the log-mode requires only a single extra operation, and computational problems are no longer limiting. Plotting of cumulative probability distributions on commercially available log-probability paper can be used to estimate lognormality and other statistical parameters.

If a population has a lognormal distribution, the mean of the logs is the log of the geometric mean of the original data, log $\bar{y}_g$. As with any normal distribution, the median is a good estimate of the mean. The arithmetic mean or average of lognormal distribution, $\bar{y}$, is alway greater than the geometric mean, $\bar{y}_g$, and frequently is twice as great. The standard deviation, s, of a lognormal distribution can be used to estimate the fraction of the time that a given value will be exceeded. Unfortunately, the absolute value of the standard deviation of the logs depends on the base of the logarithms used.

The antilog of the standard deviation that can be called the Spread Factor, S, is a better measure of the frequency of deviations from the geometeric mean and is independent of the logarithmic base.

instead of adding and subtracting a multiple of the standard deviation, one must multiply and divide by a power of the Spread Factor. Thus, 97.73 percent of the values are expected to lie between $\bar{y}_g$ times S^2 and $\bar{y}_g$ divided by S^2. Also 99.87 percent will lie below $\bar{y}_g$ times S^3. The usefulness of the lognormal distribution is illustrated in the following section which describes operating data from several advanced waste treatment plants.

South Tahoe

The South Tahoe Public Utility District (STPUD) has operated an advanced waste treatment plant to purify wastewater for export to Indian Creek Reservoir since 1968.[9] The exported water must meet regulations set by Alpine County and by the Lahontan Regional Water Control Board (LRWCB) **(Table 1)**. In addition to the required parameters, the plant regularly reports on a number of other parameters daily or several times a week. The monthly performance records from 1968 through 1974 have been analyzed statistically for selected parameters. A number of correlations between parameters that were expected to show significant relationships have been calculated.

The STPUD plant has a design capacity of 30,000 m^3/d (7.5 mgd) but operates at less than half load most of the time. The flow scheme shown in **Figure 2** includes conventional primary, secondary activated sludge, lime flocculation, first stage lime clarification to pH 11+, recarbonation to pH 9.5, second stage lime clarification, filtration through multi-media filters with additions of alum and polymer, absorption of organics in upflow granular carbon columns and final chlorination at the export pumps. The entire volume of the 17 km (ten mile) pipe to the Luther Pass pump station is used as the chlorine contact chamber. Coliforms and residual chlorine are measured at Luther Pass. Residence time in the pipe, which has a volume of 5,000 m^3 (1.3 mil. gal.) varies from four to twelve hours depending on flow.

The plant has several holding ponds including a 225,000 m^3 (60 mil. gal.) holding pond and two clay lined ballast ponds with a combined capacity of 10,000 m^3 (2.5 mil. gal). The ballast ponds are used to equalize flow between the multi-media filter and the carbon columns.

In December, 1973, a displayed manhole cover near a creek bottom delivered twice the design flow into the main sewer for two days. The excess flood water was held in storage and worked off over an entire month without upsetting the plant performance. Excess storage capacity has proved to be invaluable when maintenance was necessary on major units in the plant.

An ammonia stripping tower between the two stages of lime clarification was included in the original construction but was inadequate for the purpose and has been bypassed except for experimental purposes. Sludge is centrifugally dewatered without digestion and then incinerated. All centrates, filter backwash waters and scrubber waters are recycled through the plant. The receiving reservoir at Indian Creek is used as a public trout fishery, and surplus water is used for irrigation of pasture land for beef cattle. There is no discharge to surface streams or Lake Tahoe at any time. The period analyzed, Sept. 1, 1968, through Dec. 31, 1974, began after the initial shakedown period and represents operation under consistent management. With the exception of the last three months, the plant manager was Russell L. Culp, who was assisted by the present manager, David Calahan. Throughout the entire period, the STPUD plant has operated as a show place for Sanitary Engineers, City Managers and innumerable other visitors from all over the world. The initial construction funds were supplied in large part by Federal Grants, but the operating expenses have been borne by the district.

The raw data taken from copies of the district's monthly reports were transcribed to punch cards for subsequent handling in the computer. Appropriate steps were taken to eliminate blanks in the data and to verify apparently anomolous high values. The data were then presented as a cumulative probability plot of each parameter. From these plots it was obvious that the data, in common with many other natural parameters, did not follow a normal probability distribution. Accordingly, the data points were converted to their logarithms and lognormal plots were made. The presence of many zero and "less than" data points presented a minor problem. For the direct normal plot all "less than" points were recorded as zero. Since the logarithm of zero is undefined and cannot be handled by the program that calculates logarithms, a small arbitrary constant was added to each set of data points. The constant was chosen for each parameter to produce a useful ordinate scale and was much smaller than the least significant datum value in the set.

In **Figures 3** and **4**, plotted by the computer, the phosphate values appear as when plotted normally and as their logarithms can be compared. It is not possible to represent the points in **Figure 3** by any straight line, but the logarithm data in **Figure 4** can be represented by a straight line with a median value, M, of 0.19 mg/l and a spread factor, S, of 2.1. The median, 0.19 mg/l, is a good estimate of the geometric mean. ■

Part 2 will appear in the July issue of WSW.

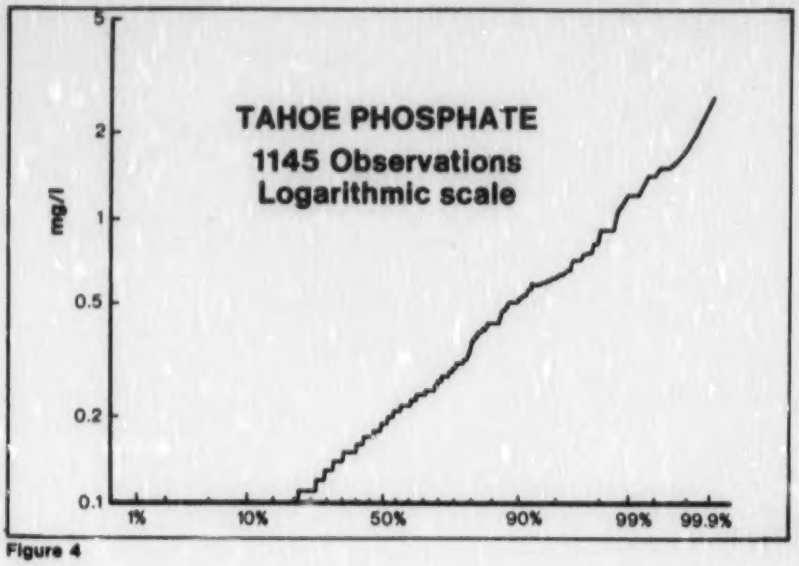


Figure 4

Table 2

South Lake Tahoe Effluent—1968-1974

Parameter	Median	98%	99%	Spread Factor*
MBAS mg/l	0.18	0.54	0.64	1.72
BOD mg/l	1.3	5.36	6.36	2.05
COD mg/l	9.6	24.5	30.7	1.57
Suspended Solids	0	0	0	-
Turbidity JTU	0.30	1.20	1.50	1.94
Phosphorus mg/l	0.19	.91	1.22	2.11
Chlorine Residual mg/l	0.90	3.0	3.6	1.77
Coliform MNP/100 ml	(0.025)	5.1	13.0	13.

* *The Spread Factor, S, is the antilog of the standard deviation of the logarithms of the original data points.*

Estimating the Reliability of Advanced Waste Treatment Part 2

by Robert B. Dean, Science Advisor, EPA
and Stanley L. Forsythe, Southwest Ohio Regional Computer Center, Cincinnati, Ohio

The following article continues the description of the analysis of data to estimate long-term reliability of advanced waste treatment based on normal statistics. The data analyzed included daily operating data covering six years of continuous operation at the South Lake Tahoe waste treatment plant plus shorter records from other plants. Part 1 appeared on page 87 of the June issue.

The rest of the data is presented on logarithmic plots only: BOD in **Figure 5**; COD in **Figure 6**; MBAS (a measure of detergents) in **Figure 7**; turbidity in **Figure 8**; coliform count at Luther Pass in **Figure 9**; and residual chlorine at Luther Pass in **Figure 10**. Stepped lines show the requirements of the LRWQCB.

Two artifacts are produced by the logarithmic conversion at the lower end of the graphs.[1] Steps in the curve caused by rounding-off of analytical data are magnified at low values, and[2] rounding-off to zero or reporting data as "less than y" takes the curve off the lower axis completely. There is evidence that the COD determination gives low results below values of about five mg/l.

Because the logarithms of low values accentuate numerical errors, the standard deviation and spread was estimated by a modification of Yost's method.[10] Values at 98, 93, 86 and 77 percent were added; four times the median (50 percent) value was subtracted; and the sum was multiplied by 2 x 0.0935 to obtain a one-sided estimate of the standard deviation. The efficiency of this estimate is somewhat less than 90 percent but is is unbiased by errors at the lower end of the distribution.

Coliform values were determined by the MPN method;[11] 94 percent of the values were reported at less than two. The best straight line fitting the logarithms of 124 values from 2 to 88 MPN as a function of the cumulative probability was calculated (**Figure 9**). This line intercepts the 50 percent or median value at 2.5 x 10^{-3} organisms/100 ml or one in four liters.

Table 2 lists the medians, the 98 and the 99 percent values together with the calculated spread factors for the chosen parameters. With the exception of the MPN, all of the spread factors lie close to two. Multiple correlations, r, between selected pairs of parameters were calculated for those days when all necessary points were available.

Surprisingly, most of the plausible correlations were so low as to be insignificant. All of the r values were less than 0.30 which means that less than ten percent of any variable is accounted for by simple correlation with any other variable. Multiple correlations were no better. Non—parametric "top corner" correlations of MPN with each variable were calculated by a modification of the tetrachoric method,[12] and there was even less apparent correlation. The maximum correlation, as expected, was between coliforms and chlorine at Luther Pass. Of 112 MPNs of two or more, 84 corresponded to chlorine values below the median value of 0.9 mg/l available chlorine. A rough estimate of the r value based on this ratio is smaller than -0.3.

The lack of significant correlation between the parameters can be restated to say that random fluctuations account for most of the spread in the data. Included in the random fluctuations will be all errors in sampling, recording, and analytical procedures, as well as all process changes that primarily influence a single variable. The plant was obviously operating under good control. The consistence of the spread factors of the raw data (except MPN which is a non-conservative parameter if bacteria can multiply after the sample has been taken) suggests that the fluctuations are random and homogeneous.

Figures 3-7 include the legal requirements for discharge from **Table 1**. It is obvious that the South Tahoe Plant is operating comfortably within the requirements. The only recorded deviation from requirements occurred in January, 1973, when four consecutive coliform values were 38, 24, 24, and 38; this was in excess of the requirements for "no more than two consecutive values greater than 23." No explanation for the deviation was reported. It was noted that the receiving reservoir was covered with ice at the time so there was obviously no public health hazard from the deviation.

To improve the reliability of a plant like South Lake Tahoe, it would be necessary to alter the design. Reducing the spread factor, S, which is a measure of the slope of the probability chart plot, is hardly possible in view of the consistent values of S for the various parameters.

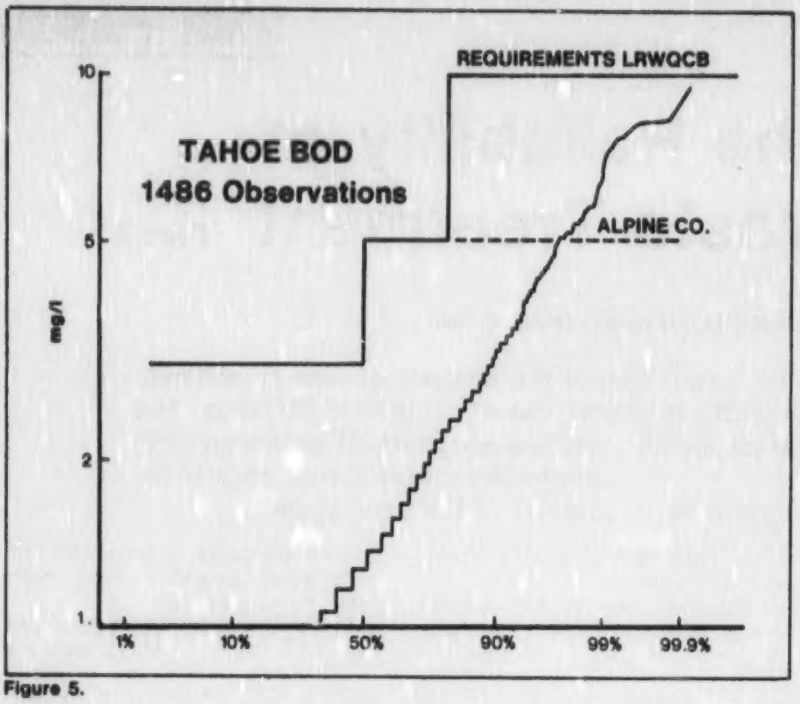
Ely, Minnesota

The Ely, Minnesota, advanced waste treatment plant is designed to remove phosphates from an existing high-rate trickling filter in an attempt to halt eutrophication of Shagawa Lake.[13] Two-stage lime clarification is followed by multi-media filtration. After recarbonation, the second-stage lime clarification is assisted with ferric chloride. Ferric chloride is also used on the filters after final neutralization with sulfuric acid to pH 7.5.

The plant removed 99 percent of the influent phosphate, producing an average of 0.043 mg/l P over an 18-month period. **Figure 11** shows the percent reliability for one year ending March 31, 1974, plotted against the logarithms of the final phosphate concentrations. The median value is 0.035 mg/l P and the spread factor, S = 1.7.

The cumulative probability plot of **Figure 11** is much closer to a straight line than the arithmetic plot. However, since the lake is an integrator of phosphates with a liquid retention time of 6 to 12 months and a longer solids retention time, the parameter of concern is the total phosphate load. This value is better represented by the arithmetic average than by the geometric mean obtained from the logarithmic plot. The geometric mean and the median underestimate the average by 13 percent in this case. However, the logarithmic presentation is much better at predicting extreme high values that occur only occasionally.

Ely reduces phosphate levels to about one fifth of the values at Tahoe but the



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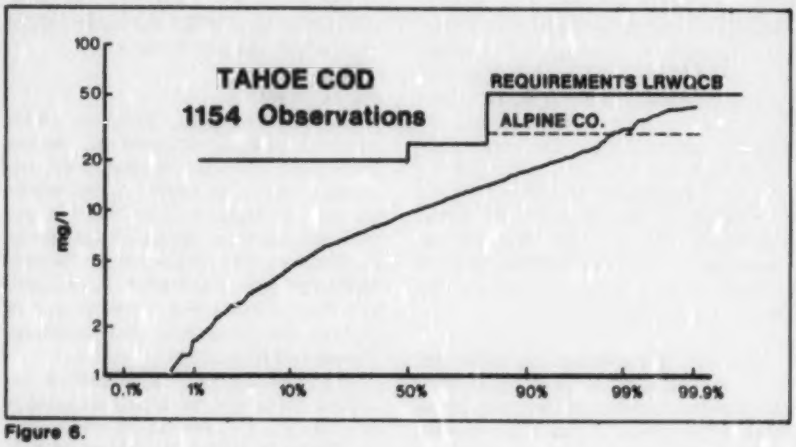

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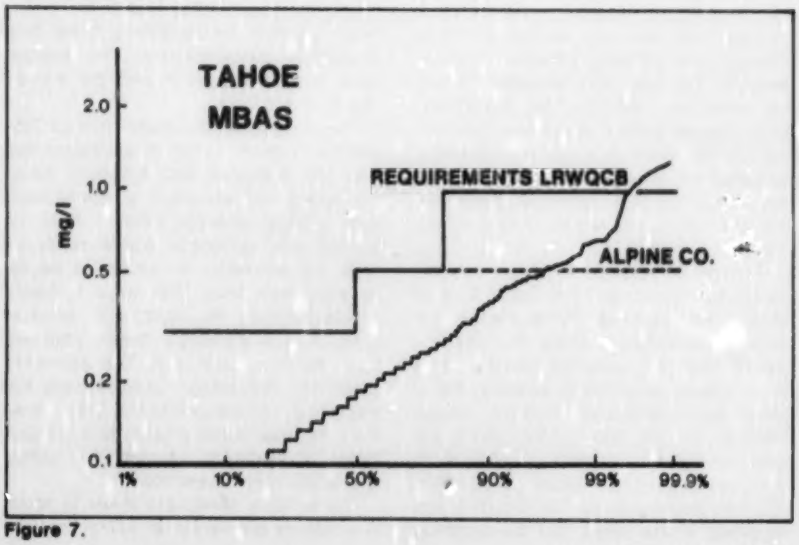


Figure 7.

spread factors are similar. The basic processes used are essentially similar and the only chemical difference seems to be that Tahoe uses alum on the filters, while Ely uses ferric chloride. A comparison of the design data in **Table 3** shows much lower secondary clarifier surface loadings at Ely. During the development of the current Ely process, additions of ferric chloride to the secondary clairifier were necessary to get low final phosphate values. The superior phosphate removal at Ely, in comparison with Tahoe, can probably be ascribed to the design and operation of the secondary lime clarifier.

At Tahoe, phosphate removal was an incidental effect of the advanced waste treatment scheme and was not required by the export regulations. There is no doubt, however, that phosphate removal at Tahoe has made possible the successful operation of Indian Creek Reservoir and therefore can be considered an indirect requirement.

Other Plants

The weekly average residual phosphorus levels reported by Elfving and the Forsbergs[14] were obtained from the authors for the five Swedish plants employing chemical precipitation. The data were plotted as normal (arithmetic) and lognormal cumulative diagrams. Ten months daily data from the Grand Haven, Michigan, plant were similarly plotted.[15] In every case the lognormal plot was at least as good as the normal plot and in most cases obviously better. In each case the K-S criteria for normality of the arithmetic plot was exceeded at the five percent level. The statistics are given in **Table 4.** All six chemical plants are removing phosphate below one mg/l on the average, but all exceed 1.0 mg/l from time to time. The spread factors are all close to their average of 1.7 which is in close agreement with the spread factor at Ely. Ely, however, reduces phosphates to one tenth of the level achieved by the other plants, and it is about as likely for Ely to exceed 0.1 mg/l as it is for the other plants to exceed one mg/l.

Biological treatment without chemical precipitation gives phosphorus levels in the effluent with spread factors much closer to 1.0. The data of Elfving, et al.[14] for Motala has S = 1.15, and Grand Haven[15] has S = 1.19 before chemical treatment. When the spread factor is so close to one, both normal and lognormal statistics will fit the data well.

Wheatland[16] reports data from 14 large treatment plants in terms of the 50th percentile (median) and 95th percentile (which lies at 1.65 standard deviations from the median if the data are normalized). From his data one can calculate spread factors of 1.4 to 1.5 for BOD and SS. Higher spread factors near 2.0 are found for residual ammonia in plants that nitrify and for nitrate in plants where the NO_3-N is low.

Wheatland, unfortunately, confused the median with the mean which leads to significant errors if the data is lognormal with spread factors as large as he finds. Porter[11] presented a graph of the ratio of percentiles to mean concentrations based on the same data used by Wheatland. Assuming lognormal statistics, the spread factor is 1.54.

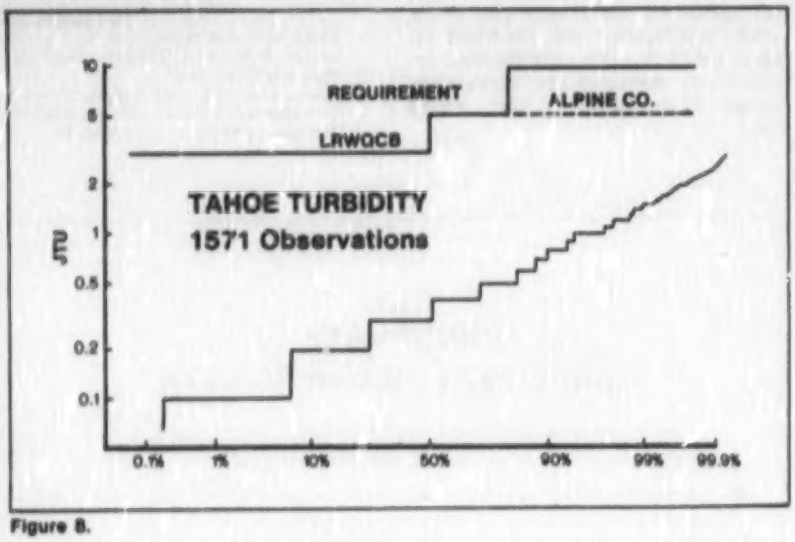
Again there appears to be confusion between the mean and the median. Porter specifically states that "the mean (arithmetic average) is the simplest (and most reliable) statistical value to estimate." His **Figure 1** equates the mean with the 50th percentile (median). Yet the 95th percentile corresponds to a spread factor of 1.54, and the mean will be nearly ten percent greater than the median according to Aitchison and Brown.[1]

Discussion

Several papers have dealt with the statistical distribution of extreme values. Some recent contributions have dealt with the application of statistical concepts to the setting of standards for wastewater discharges,[16,17,18] but, with few exceptions, legal requirements have not included statistical considerations.

If the performance of a plant obeys normal or lognormal statistics, there is a real probability of exceeding any finite upper limit, although the probability may be very small. The requirement that a parameter *never* exceed a designated value is unrealistic from an operational point of view no matter how attractive it may appear to a legal mind. If the requirement is rephrased to permit the parameter to exceed the designated value not more than one day in ten thousand, or once in about 30 years, we can at least calculate the required performance of the plant. If the Spread Factor is 2.0, the statistical tables show that the mean must be less than eight percent of the upper limit. If, instead, the designated upper limit can be exceeded one day in a thousand, the mean can be 12 percent of the upper limit and for one day in a hundred it can be 20 percent of the limit. In any case, a plant will be designed as a compromise between the cost of meeting the regulation and the cost of not meeting it, that is, the cost of expected fines and other adverse results of exceeding the requirement.

Stating the requirements in terms of the one month average makes it easier to meet specifications because there is a chance to take corrective action. The arithmetic average may give a better measure than the geometric mean for total discharge of a pollutant that accumulates, such as phosphates in a lake. However, the use of a monthly average BOD might not protect a stream if a few days of high BOD resulted in zero DO and killed all the fish. The decision as to how specifications are set should be based on the effects of violations and, ultimately, on the internal cost of compliance, in



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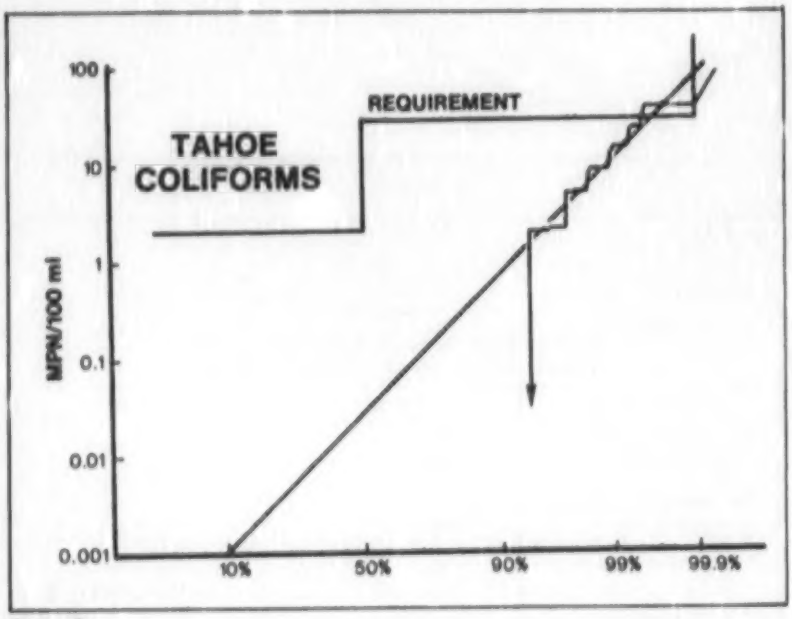

Figure 9.

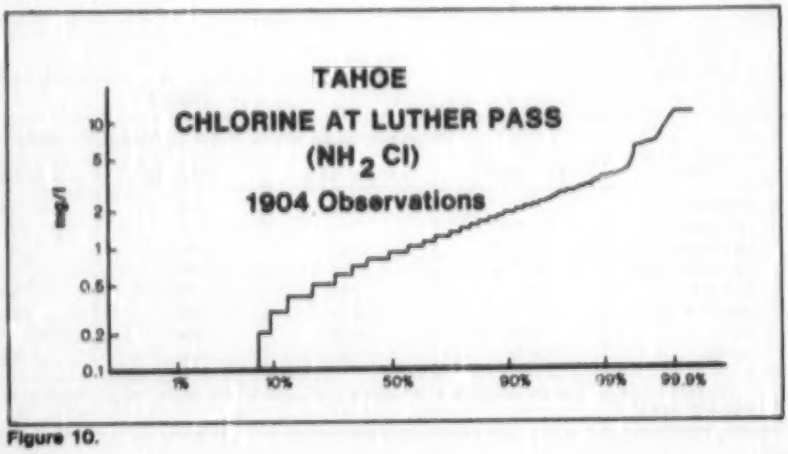

Figure 10.

comparison with the external cost of violation. A recognition that real plants release pollutants whose concentrations are lognormally distributed can increase the validity of extrapolations from existing data.

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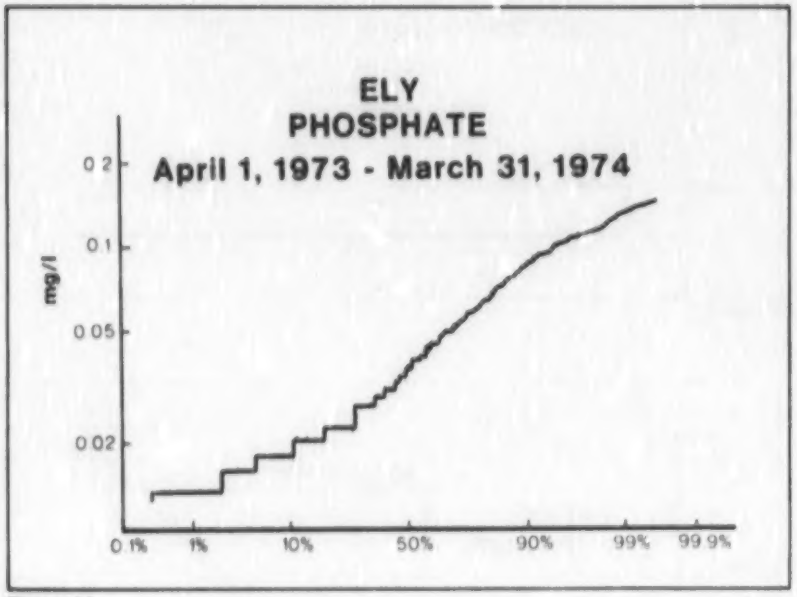

Figure 11.

Table 3

Comparison of Tahoe and Ely Treatment Plant Clarification and Filtration Design Parameters

Process Design	Tahoe[a]	Ely[15]
Primary lime clarifier		
Overflow rate	40 m/d	25 m/d
pH	11.0	11.8-12.0
Secondary lime clarifier		
Overflow rate	100 m/d	30 m/d
pH	9.6	9.6
Chemical additions	CO_2	CO_2 $FeCl_3$-6mg/l Fe
Multimedia filters		
Surface loading rate	0.2 m/d	0.15 m/d
Chemical addition	Alum + Polymer	H_2SO_4 + $FeCl_3$ 3 mg/l Fe
pH	7.6	7.5

Table 4

Phosphorus Residuals After Chemical Precipitation in mg/l

Plant	Chemical[a]	Number of pts.	Average	Standard Dev.	Geometric Mean	Spread Factor
Sjalevad	Al III	51	.48	.34	.35	1.85
Leksand	Ca III[b]	21	.36	.20	.30	1.62
Borlange	Fe $^{+3}$ III	52	.91	.43	.72	1.87
Vikmanshytten	Fe $^{+2}$ II	52	.61	.27	.53	1.51
Eolshall	Al I	52	.65	.33	.54	1.64
Grand Haven	Fe $^{+2}$ I	285	.85	.40	.80	1.54
Ely	Ca III	365	.043	.024	.035	1.70
Tahoe	Ca III	1145	.20	.18	.19	2.11

[a] *I, II, and III refer to chemical additions at the primary, secondary, and tertiary stages respectively.*
[b] *Ca=Ca (OH)$_2$*

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